Thermal analysis as a microstructure prediction tool for A356 aluminium parts solidified under various cooling conditions

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Abstract: Thermal analysis technique has been used for a long time, in both ferrous and nonferrous industries for evaluating the metallurgical quality of the liquid metal before casting. However, obtaining a proper microstructure in a standard cup does not ensure that the microstructure is correct in real parts which may solidify at very different cooling rates. For this study, alloy A356 with different metal quality in terms of modification and grain refinement was tested. Different cooling rates were obtained by using cylindrical test samples with various diameters cast in sand and metallic moulds. The correlation between microstructure features such as grain size, modification rate and secondary dendrite arm spacing (SDAS) measured in the standard thermal analysis cup with those obtained in the cylindrical test parts has been investigated. Thus, knowing the thermal modulus and the mould type it is possible to establish the required grain size and modification rate in the standard cup in order to get a desired structure in a real part. Corrective actions can then be taken in order to improve the metallurgical quality before casting the part.

Key words: A356 aluminium alloy; solidification; thermal analysis; grain size; modification rate

Aluminium silicon alloys are one of the most used groups of foundry alloys due to their excellent castability and good mechanical properties. It is known that their mechanical properties, and in particular the elongation, are significantly improved by reducing the secondary dendrite arm spacing (SDAS) or by increasing modification grade of eutectic silicon particles. Another common treatment of liquid melts is the grain refinement which exerts a positive influence on several properties of cast alloys such as porosity and hot tearing tendency [1-3].

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Thermal analysis technique has been used for a long time, in both ferrous and nonferrous industries for evaluating the metallurgical quality of the liquid metal before casting. Many researchers have tried to correlate parameters of the cooling curves with microstructure features [3-11], alloy A356 being one of the most studied alloys. Several parameters associated with primary solidification of the aluminium rich solution (Al) have been suggested to assess grain refinement [4,10,11], such as under-cooling, recalescence or time related parameters. For modification rate prediction the eutectic temperature depression in reference to that for unmodified alloy, the recalescence (difference between maximum and minimum eutectic temperatures) or time related parameters have been used [8,11].

However, little effort has been made on predicting the microstructure in real parts which is influenced by the differences in cooling rate associated to the modulus of the casting and/or mould materials. In the present work an attempt was made to correlate the results of thermal analysis parameters and microstructure in standard cup with the microstructure obtained in test samples with different thermal modulus and mould materials. Alloy A356 with different grain refiner and modifier additions has been tested at cooling rates varying between 1.5 and 30 ℃/s.

1 Experimental procedure

The chemical compositions of the alloys cast in this study are listed in Table 1. The additions of Ti and Sr were varied in order to obtain different modification rates and grain sizes. All the tests were carried out in an aluminium foundry with metal from the production line that includes a certain amount of internal returns. Alloy 1 was cast without Ti and Sr addition (casting 1A) as well as with half amount of normal grain refiner addition (casting 1B). The small Sr content in alloy 1 is due to the returns. Alloys 2 and 3 were elaborated with the usual Ti refiner and Sr modifier additions of the foundry.

Table 1: Chemical analysis of the investigated A356 alloys

	Chemical composition (wt.%)							
Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
1A	7.2	0.11	<0.01	<0.01	0.41	<0.01	0.11	0.003
1B	7.3	0.11	<0.01	<0.01	0.41	<0.01	0.12	0.003
2	7.0	0.16	0.01	<0.01	0.35	0.02	0.16	0.010
3	6.3	0.13	0.03	<0.01	0.32	0.05	0.19	0.013

The four alloys were cast in sand and metallic moulds that are schematically shown in Fig. 1. These moulds were designed in such a way that the height of each cylinder is equal to its diameter. The corresponding thermal modulus of each cylinder is listed in Table 2. At the centre of each cylinder a thermocouple was located for cooling curve recording. No data was obtained for alloy 1A cast in the metallic mould with modulus 0.4 because the thermocouple failed.

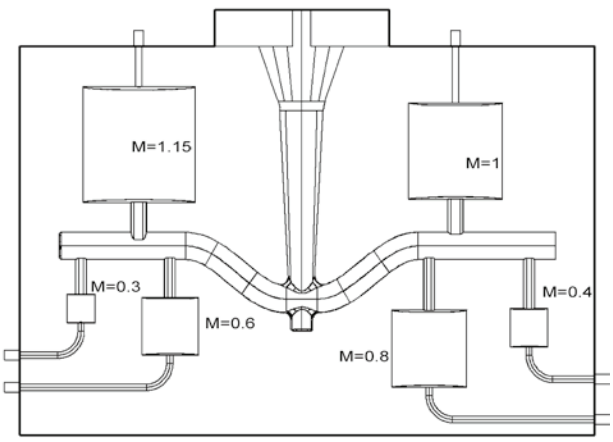


Fig. 1: Schematic of metal moulds used for the cylindrical test samples *(The design was similar to the sand moulds)*

Table 2: Thermal modulus of the cylindrical test samples

Mould	Thermal modulus (cm)						
Sand	1.5	1.15	1	0.8	0.6	0.4	-
Metal	-	1.15	1	0.8	0.6	0.4	0.3

For each alloy, a cooling curve was recorded with a standard sand cups (TA cup with a calculated thermal modulus of 0.605 cm) and analyzed using the Thermolan–Al system [12]. The system is based on the thermal analysis technique and has been shown to be capable of predicting grain size, modification rate and SDAS in alloy A357 by analysing the parameters of the solidification curve [13]. The prediction for alloy A356 is still in process of optimization in the line of the present work. The characteristic parameters of the cooling curves are the following ones (see Fig. 2):

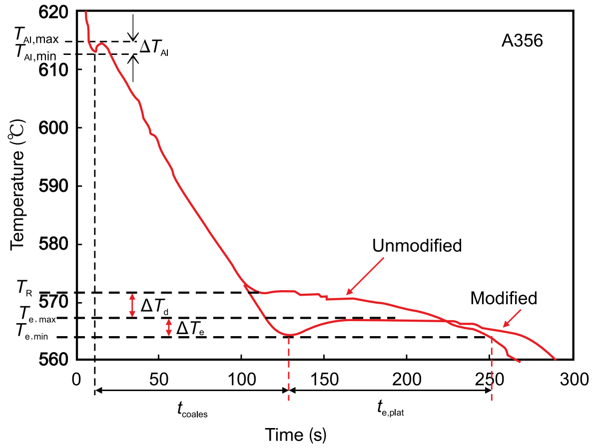


Fig. 2: Nomenclature of the characteristic parameters taken from the cooling curves

- For the nucleation of the primary (Al) phase, the minimum $T_{Al,min}$ and maximum $T_{Al,max}$ temperatures from which the recalescence ΔT_{Al} is calculated;
- For the eutectic reaction, the minimum $T_{e,min}$ and the maximum $T_{e,max}$ temperatures, and the recalescence ΔT_e;
- Time related to parameters are $t_{e,plat}$ and t_{coales}, i.e. the duration of the eutectic plateau and the time difference between the minimum temperature for (Al) nucleation and eutectic transformation;
- $\Delta T_d = T_R - T_{e,max}$ is the eutectic depression calculated using as reference the maximum eutectic temperature for the unmodified alloy, T_R.

The value of T_R used in the present work was calculated by means of the equation suggested by Mondolfo [14]:

$$T_R = 577 - \frac{12.5}{w_{Si}} \cdot (4.43 \cdot w_{Mg} + 1.43 \cdot w_{Fe} + 1.93 \cdot w_{Cu} + 1.7 \cdot w_{Zn} + 3.0 \cdot w_{Mn} + 4.0 \cdot w_{Ni})$$

where w_i is the weight fraction in species i of the alloy. The temperatures thus calculated are very similar to the alloys studied.

SDAS measurements were performed using a Leica Image Analyser. About 30 measurements were made for each experimental condition to get an average SDAS value. Grains were observed by optical microscopy under polarized light after electrolytic Barker etching of the samples. The grain size GS was then determined by the linear intercept method. Modification rate was evaluated by quantitative image analysis using the silicon particle diameter as a measure of the Si modification. The six modification rate patterns published by Apelian et al. [8] were used to determine the reference particle diameter for each modification level following the same procedure as that used by MacKay et al. [13]

2 Results and discussion

2. 1 Thermal analysis cup

The results of the microscopic examination of the thermal analysis cups and the parameters obtained from the corresponding cooling curves are presented in Table 3. A correlation is observed between liquidus undercooling ΔT_{Al} and grain size. As the grain size increases from 0.31 mm to 2.3 mm the liquidus undercooling increases from 0 to 1.5℃.

The ΔT_d values calculated are shown in Table 3. The variation in chemical composition does not allow observing the increase of the eutectic temperature depression with modification reported by other authors [6, 8].

Table 3: Microstructure and cooling curve data of the thermal analysis cups

Alloy	Microstructure			Thermal analysis parameters							
	SDAS (μm)	GS (mm)	Modification level	$T_{Al,min}$(℃)	ΔT_{Al}(℃)	$T_{R,cal}$(℃)	$T_{e,min}$(℃)	ΔT_e(℃)	ΔT_d(℃)	$t_{e,plat}$(s)	t_{coales}(s)
1A	53.9	2.30	2.3	606.4	1.5	573.6	562.3	2.6	8.1	125.8	124.1
1B	61.1	0.92	2.0	611.5	0.7	573.6	562.4	2.3	8.0	115.5	126.9
2	56.8	0.52	3.2	614.1	0.1	573.8	565.5	2.8	5.3	135.5	132.7
3	57.3	0.31	3.4	613.2	0.0	573.5	566.4	2.2	4.9	128.9	119.2

2.2 Effect of thermal modulus and mould material

The effects of thermal modulus and mould type on the solidification are illustrated by the cooling curves recorded with alloy 2 that are reproduced in the two graphs in Fig. 3. As the cooling rate is increased, the solidification time, the eutectic temperature and the eutectic plateau duration all decrease.

On both graphs, the cooling curve recorded with the TA cup has been superimposed. The solidification time of the TA cup is longer than that of any of the cylinders cast in metallic mould and in between the curves of the cylinders with modulus 0.8 and 1 for sand casting. This indicates that heat transfer is higher in sand moulds than in the TA cups, and this may come from differences in sand conductivity.

The SDAS values measured on the cylinders are listed in Table 4 and have been plotted in Fig. 4 as function of the modulus. It is seen that the values follow two different behaviours depending on the mould material, larger SDAS being observed on samples solidified in sand mould when compared to those cast in metallic mould. This reflects the fact that SDAS depends on the cooling rate, and more specifically

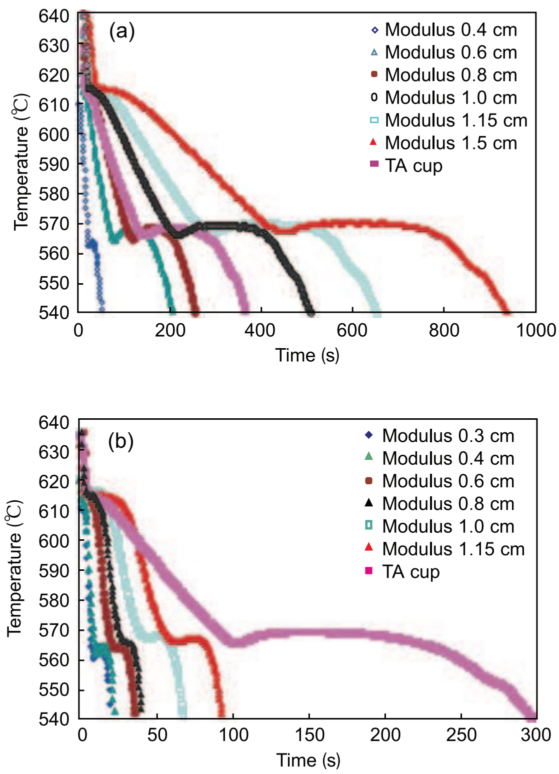


Fig. 3: Cooling curves for alloy 2 obtained for cylindrical castings of different modulus and standard TA cup (a) sand mould; (b) metallic mould

Table 4: Results of SDAS measurements (μm)

Alloy	1A		1B		2		3	
Mould	Sand	Metal	Sand	Metal	Sand	Metal	Sand	Metal
Modulus(cm)								
1.5	73.2	-	90.3	-	86.3	-	98.9	-
1.15	67.8	43.3	90.2	37.4	71.8	42.7	77.5	40.9
1	58.8	36.6	76.0	34.5	61.1	37.0	64.0	30.1
0.8	52.5	27.7	62.5	30.5	54.7	30.6	57.2	29.5
0.6	43.4	30.1	48.0	27.0	51.4	27.9	42.8	28.4
0.4	40.6	-	38.0	20.8	29.6	21.9	34.6	21.0
0.3	-	19.7	-	20.8	-	20.6	-	18.8

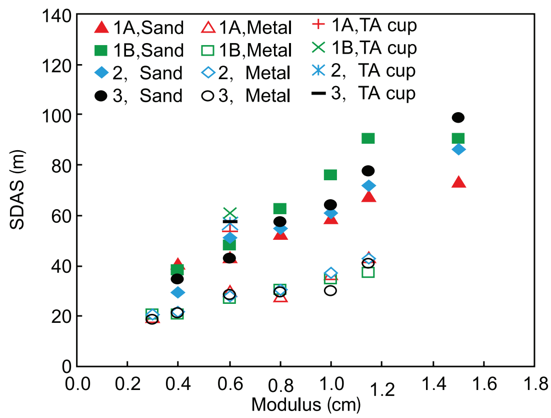


Fig 4: SDAS of the cylinder test samples *vs* thermal modulus *(The data for TA cups are also included)*

on the solidification time. In the present study, the time during which the dendrite arms may grow by coalescence is t_{coales}, considering that coalescence stops when the eutectic starts forming. As a matter of fact, all data could be fitted by a unique equation SDAS = $9.3(t_{coales})^{0.38}$ with a correlation coefficient R^2 equal to 0.96.

The results of grain refinement listed in Table 5 are shown in the graphs of Fig. 5. Grain refinement is illustrated by the micrographs in Fig. 6 that were made on the TA cups. The following tendencies can be observed:

• In the case very fine grains were observed in the TA cup (alloy 3, GS = 0.31 mm), very fine grains with size in the range 0.3 to 0.4 mm are obtained in the cylinders independent of the thermal modulus or mould material.

• When fine grains are obtained in the TA cup (alloy 2, GS = 0.52 mm), very fine grains (about 0.3 mm) are observed in the cylinders cast in metallic moulds while the grains are coarser in sand moulds between 0.44 and 0.74 mm. In this latter case, the grain size is more sensitive to thermal modulus.

• For medium and coarse grain sizes in the TA cup (alloys 1A and 1B, GS = 0.92 to 2.3 mm), the grain size depends on the thermal modulus. An increase in grain size is observed as the thermal modulus is increased or the mould material is changed from metal to sand.

Thus, knowing the grain size prediction from the TA sample cup, the mould type and the thermal modulus, it is possible to have an idea of the grain size that might be expected in different sections of a real part. However, more work is necessary in order to ascertain empirical expressions used for that prediction.

Table 5: Grain size values GS (mm)

Alloy	1A		1B		2		3	
Mould	Sand	Metal	Sand	Metal	Sand	Metal	Sand	Metal
Modulus(cm)								
1.5	4.8	-	1.1	-	0.74	-	0.39	-
1.15	4.5	3.4	1.05	0.72	0.72	0.31	0.38	0.38
1	4.0	3.4	0.99	0.65	0.66	0.26	0.32	0.37
0.8	4.8	3.5	0.89	0.60	0.55	0.24	0.34	0.35
0.6	2.2	3.4	0.73	0.50	0.50	0.27	0.27	0.35
0.4	1.2	-	0.51	0.45	0.44	0.60	0.25	0.32
0.3	-	1.6	-	0.38	-	0.55	-	0.27

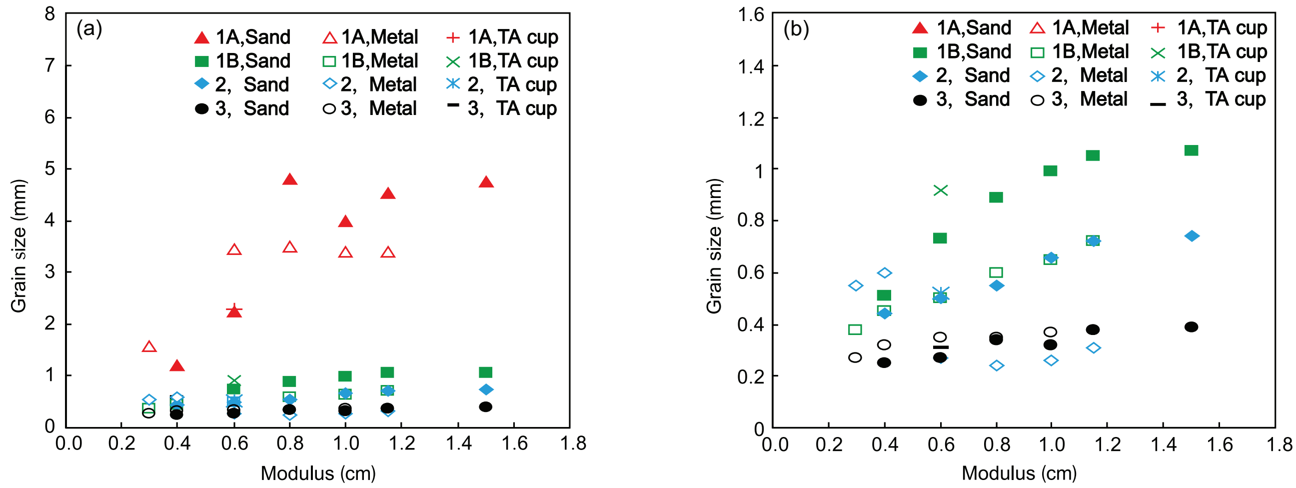
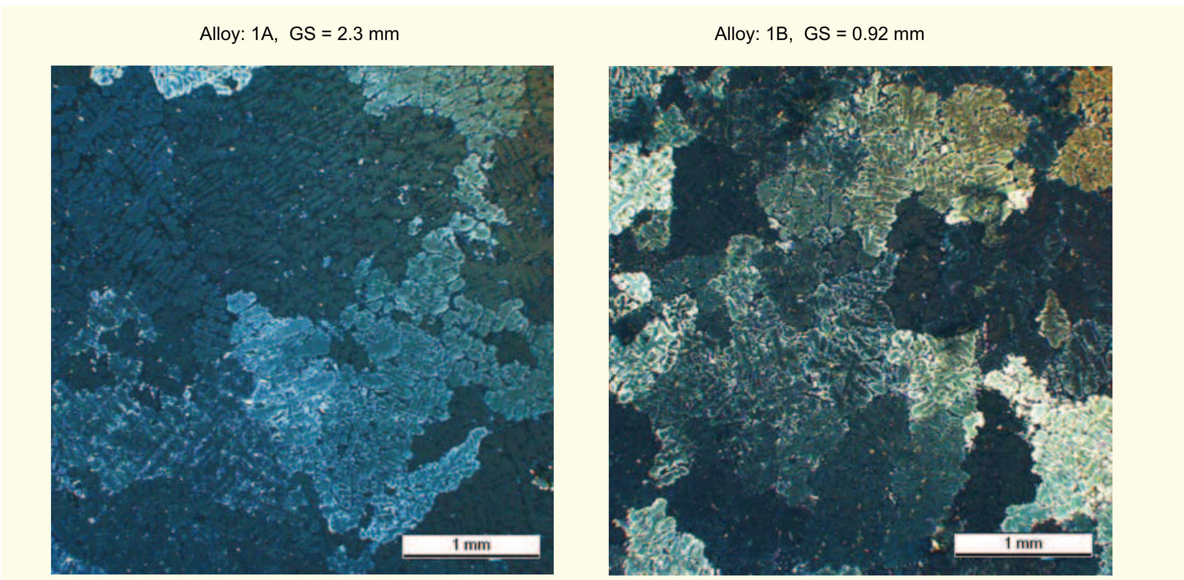


Fig. 5: Grain size values *vs* thermal modulus (a) and an enlargement for small grain sizes (b) *(The data for TA cups are also included)*



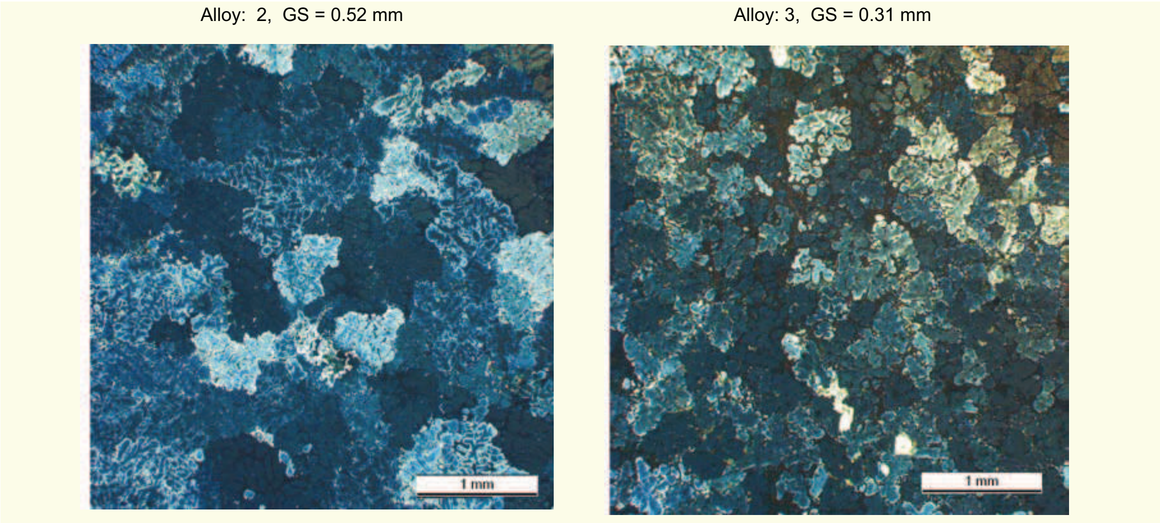


Fig. 6: Grain size observed in the TA cup for each analyzed alloy

Another interesting observation is that without refiner addition during the melting process of alloy 1A, the Ti present in the alloy (0.11wt.%) results from the ingot and returns. It was noticed that poor grain refinement is achieved even with metallic moulds and this indicates that the Ti compounds from the ingot and returns are not active nuclei. By addition of half amount of the normal grain refiner addition used in the foundry, the Ti content was increased slightly from 0.11% to 0.12%, but the grain size in the thermal analysis sample was reduced from 2.3 to 0.92 mm. Thus, chemical analysis alone is not enough to control grain refinement in the melt, since it does not tell anything about the effectiveness of the grain refiner.

In some cases a small coarsening of the grains was observed in the metallic moulds with smallest modules, 0.3 and 0.4 respectively (alloy 2). This observation is under further investigation.

The results of the microscopic examination of the eutectic modification of the cylindrical test samples listed in Table 6 are plotted in Fig. 7 and illustrated with the micrographs in Fig. 8. The main results are:

• Parts cast in metallic moulds: A good modification level is observed in all the alloys cast into metallic moulds, all values being equal or above a modification level of 4. As the thermal modulus decreases and the Sr content increases, a small improvement of the eutectic Si modification is found.

Table 6: Results of modification level measurements

Alloy	1A		1B		2		3	
Mould	Sand	Metal	Sand	Metal	Sand	Metal	Sand	Metal
Modulus(cm)								
1.5	2.3	-	1.8	-	3.0	-	3.2	-
1.15	2.4	4.0	2.0	4.0	3.1	4.0	3.2	4.3
1	2.6	4.0	2.1	4.0	3.5	4.5	3.2	4.8
0.8	3.0	4.2	2.3	4.5	3.5	4.5	3.4	4.9
0.6	2.8	4.5	3.0	4.4	3.5	4.7	3.4	5.0
0.4	3.5	-	3.5	5.0	4.8	5.0	3.7	5.1
0.3	-	5.2	-	5.0	-	5.3	-	5.1

• Parts cast in sand moulds: Low (level 2) and medium (level 3 or 4) Si modification is found for sand moulds. In this type of moulds the effect of Sr addition becomes more important. Accordingly, a moderate modification level above 3 can be obtained only by Sr addition and/or for small thermal modulus (0.4).

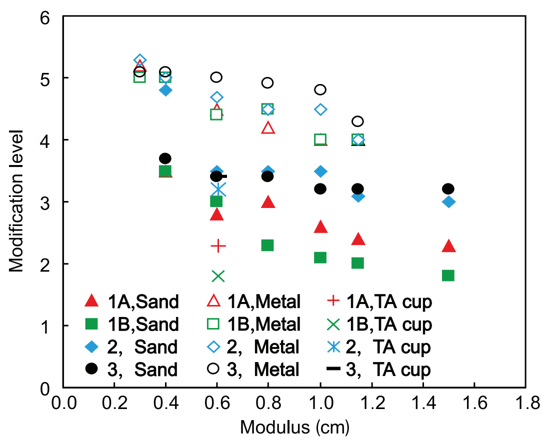


Fig. 7: Modification level *vs* modulus

3 Conclusions

The influence of cooling rate in alloy A356 has been investigated. Cooling rates between 1.5 and 30 ℃/s have been obtained by varying the thermal modulus of cylindrical test samples cast in sand or metallic moulds. The microstructure of the samples has been related to the microstructure and cooling curve parameters measured in standard thermal analysis cup. Four alloys with different metallurgical qualities in terms of grain refinement and modification have been analysed leading to the following conclusions:

(1) Knowing the microstructure in the TA cup, it is possible to have an idea of the microstructure that can be expected in a real part according to its thermal modulus and to the mould type.

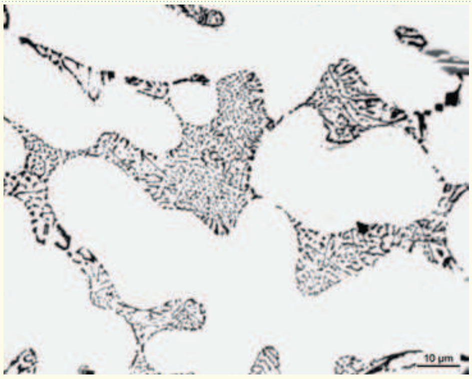
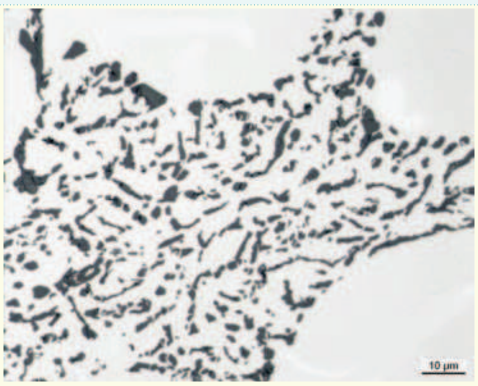
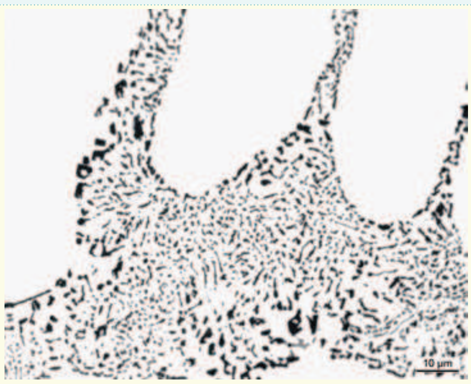
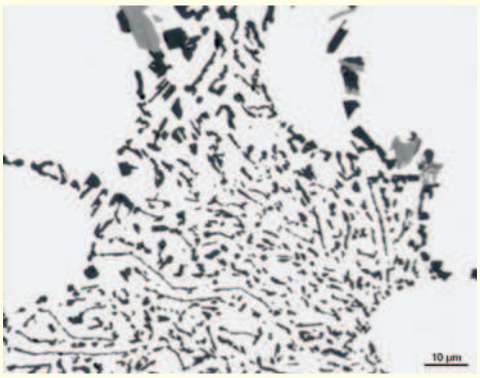
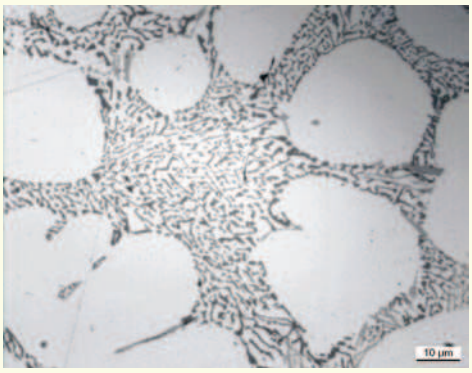
Modulus	Alloy 1A	
	Sand mould	Metallic mould
1.15 cm	 M = 2.4	 M = 4.0
0.4 cm	 M = 3.5	 M = 5.2 (modulus 0.3)
Modulus	Alloy 3	
	Sand mould	Metallic mould
1.15 cm	 M = 3.2	 M = 4.3
0.4 cm	 M = 3.7	 M = 5.1

Fig. 8: Illustration of the modification observed in the cylindrical test samples

(2) If grain refinement is optimum (about 0.3 mm in the TA cup), fine grains can be expected independent of the cooling rate imposed by the thermal modulus and/or mould type.

(3) As the grains in the TA cup become coarser, the cooling rate becomes more important. For a grain size of 0.5 mm in the TA cup still very fine grains are observed in cylinders cast in metallic moulds while in sand moulds grain size is between 0.4 and 0.7 mm depending on the modulus.

(4) If the metal is not correctly refined large grains are observed even in metallic moulds.

(5) Grain refinement can not be ascertained from the Ti content in the alloy alone; the effectiveness of the Ti nucleants should be checked from the thermal analysis curve.

(6) Good modification levels (between levels 4 and 5) are achieved in the cylinders cast in metallic moulds, even for the poorly modified alloy (level 2 in TA sample).

(7) A correct Sr modification becomes more important for parts cast in sand moulds. Reasonable modification levels (between 3 and 4) are obtained when the metal is well modified, whereas low modification is found (< 3) in the poorly modified alloy (0.003wt.%Sr), except for the smallest thermal modulus.

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